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# On the Interaction Between Cosmic Rays and Dark Matter Molecular Clouds in the Milky Way. 1 Basic Considerations

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## ABSTRACT

We explore some basic observational consequences of assuming that the dark matter in the Milky Way consists mainly of molecular clouds, and that cosmic rays can penetrate these clouds. In a favoured model of the clouds, this penetration would have the following consequences, all of which agree with observation:

- (i) cosmic ray nuclei would be fragmented when they enter a cloud, giving them a lifetime in the Galaxy of  $10^{15}$  sec (for relativistic nuclei).
- (ii) Pionic  $\gamma$  rays emitted by the clouds, after pp collisions, would have a flux in the galactic plane comparable to the flux from known sources for photon energies  $> \sim 1$  GeV.
- (iii) The heat input into the clouds from cosmic rays would be re-radiated mainly in the far infra-red. The resulting radiation background agrees, in both intensity and spectrum in different directions, with a known excess in the far  $i - r$  background of the galaxy over emission by warm dust.

**Key words:** ISM - clouds - cosmic rays - dark matter - gamma rays - infra-red continuum.

## 1 INTRODUCTION

Various authors (Pfenninger, Combes & Martinet 1994, De Paolis et al 1995, Gerhard & Silk 1996) have proposed a viable model in which most of the dark matter in the Milky Way is baryonic and consists of a population of self-gravitating clouds of mainly molecular hydrogen (possibly accompanied by clusters of brown dwarfs). A favoured set of parameters for these clouds is: mass  $M \sim 10^{-3} M_{\odot}$ , radius  $r \sim 10^{14}$  cm, temperature  $T \sim 10$  K, velocity dispersion  $\bar{v} \sim 200 \text{ km} \cdot \text{sec}^{-1}$  for a halo distribution with a covering factor  $f \sim 5 \times 10^{-4}$  (Draine 1998).

One way of testing this model observationally is to search for effects arising from the interaction of cosmic rays with these clouds. This paper is the first of a series in which such an interaction is investigated. In it only the basic implications of the interaction are considered. The many details involved will be examined in later papers of this series.

At the outset it has to be decided whether cosmic rays can penetrate the clouds. This question is discussed in section 4. If the penetration does occur, a number of observable effects would arise for the favoured model of the clouds. In this paper the following effects are discussed:

- (i) Cosmic ray nuclei would be completely fragmented when they penetrate a cloud. This process may determine the survival time of the nuclei in the Galaxy, rather than their leaking out of a confinement volume as envisaged in the usual picture of cosmic ray propagation. It is straight-

forward to calculate the mean survival time  $t_0$ , and for the favoured cloud model one finds for relativistic nuclei that  $t_0 \sim 10^{15}$  secs. This value agrees well with that derived from observations of the radioactive cosmic ray nuclei  $\text{Be}^{10}$  and  $\text{Al}^{26}$ . By contrast, the survival time in the leakage models cannot be calculated a priori.

(ii) Cosmic ray proton collisions with protons in the clouds would lead to the production of neutral pions which would rapidly decay into  $\gamma$  rays. In the favoured model for the clouds the resulting integrated  $\gamma$  ray flux in the galactic plane would be comparable to the  $\gamma$  ray flux due to known sources. The clouds would be optically thick for hadronic interactions of incident protons with energies exceeding 1 GeV, and allowance must be made for this in calculating the resulting  $\gamma$  ray flux. A rough estimate of this optical depth effect suggests that the excess  $\gamma$  ray flux in the galactic plane would be noticeable only at photon energies exceeding  $\sim 1$  GeV, and that this excess should be somewhere between a factor 1 and 2. This estimate agrees with analyses of the EGRET data, which find an unexplained excess in the  $\gamma$  ray flux in the galactic plane of 60% for  $\gamma$  ray energies exceeding 1 GeV.

(iii) Cosmic ray collisions would also heat the clouds, and this heat would be mainly re-radiated in the far infra-red via molecular line emission. It is convenient to estimate the resulting diffuse far  $i - r$  radiation  $F_{ir}$  in the galactic plane by relating the heat input into a cloud to its emission rate  $F_{\gamma}$  for  $\gamma$  rays with energies exceeding 1 GeV. One obtains in this

way a conversion factor  $\sim 0.06$  ergs per  $\gamma$  ray. One can then use this conversion factor to derive  $F_{ir}$  from  $F_\gamma$ . We find that  $F_{ir} \sim 2 \times 10^{-5}$  ergs  $\text{cm}^{-2} \text{sec}^{-2}$  in a sample direction in the galactic plane. This intensity, and the spectrum of the excess, agree with the properties of a known excess in the far  $i-r$  emissivity of the Galaxy over that expected for a standard warm interstellar dust model. The origin of this observed excess is controversial, and we here suggest that it is due to the emission from "dark matter" molecular clouds powered by cosmic rays. In a later paper in this series we study in detail the relation between the intensity and the spectrum of the far  $i-r$  and  $\gamma$  ray emissivities of the Galaxy as a function of the direction of observation.

These ideas can also be tested in the future when detectors, such as Planck, will be able to observe point sources with a flux density greater than 1 Jy at  $850\mu$ , even if only a few such sources exist over the whole sky. In the present model there would be about 10 such cloud sources, with correspondingly larger numbers of fainter sources. These sources should have  $S_{450} \lesssim S_{850}$ , in contrast to external galaxies which have  $S_{450} > S_{850}$ . These predictions could lead to a decisive test of the model.

(iv) At high galactic latitudes the averaged column density of the clouds is about ten times greater than that of the visible interstellar matter. In this case it has already been pointed out by De Paolis et al (1999 a, b) that the recently discovered  $\gamma$  ray halo of the Galaxy (Dixon et al 1998) may be due to the interaction of cosmic rays with clouds in the halo. The implied far  $i-r$  emission at high galactic latitudes then turns out to be of the same order as the observed galactic far  $i-r$  excess in those directions.

The plan of the paper is as follows: section 2 is concerned with some properties of the so-called Extreme Scattering Events (ESE's) which are used to determine several parameters of the molecular cloud model. In section 3 we consider the formation epoch of the clouds which is a partial guide to their likely metallicity. This metallicity plays a crucial role in their far  $i-r$  emissivity. Section 4 is devoted to a study of ionisation, pionisation and spallation losses of the cosmic rays penetrating the clouds, and the value of the collision time  $t_0$  is determined. In section 5 the temperature  $T$  of a cloud is derived and also the ratio  $F_{ir}/F_\gamma$ . The observed  $\gamma$  ray emission of the Galaxy and its implications for the cloud model are considered in section 6. This is followed in section 7 by a discussion of the basic far  $i-r$  properties of the model which are then compared with observation. Finally section 8 contains our conclusions.

## 2 EXTREME SCATTERING EVENTS AND DARK MATTER MOLECULAR CLOUDS.

Extreme Scattering Events (ESE's) (Fiedler et al 1987) consist of occasional large disturbances to the radio emission of point sources. They are believed to be due to plasma irregularities located in the Galaxy which drift across the radio sources. The origin of these irregularities is not known. Walker & Wardle (1998) suggested that they are the skins of dark matter molecular clouds (hereafter MC's) which have been ionised by interstellar ultra-violet radiation. One advantage of this suggestion, as Walker & Wardle pointed out, is that it leads to a determination of several parameters of the MC's, including the crucial result that their total mass

is comparable to the dark matter mass of the Galaxy (see also Draine 1998).

The ESE's can be used to determine a further parameter of the MC's, namely the scale height  $H$  of their distribution in the Galaxy. This scale height helps to determine the number density  $n$  of MC's in the galactic plane. This density  $n$  enters into the calculation of both the collision time  $t_0$  and the integrated  $\gamma$  ray emissivity of the clouds in the galactic plane.

The angular distribution of ESE's in the Galaxy has recently been considered by Lazio (1999). His statistical analysis led him to the conclusion that ESE's are a disk rather than a halo population, and so have nothing to do with the dark matter problem. However, at my suggestion, he kindly considered the intermediate possibility of a flattened halo distribution for the ESE's, and in particular the value 3 kpc for  $H$ . His Monte Carlo calculations found (private communication) that if the radius of the MC distribution in the galactic plane is 10 kpc, and  $H$  is 3 kpc, then the quadrupole moment  $q$  of their distribution is within one standard deviation of the value of  $q$  which he derived from the ESE data. For a radius of 25 kpc the difference in the  $q$ 's lies within  $1.5\sigma$ . Accordingly we will adopt the value 3 kpc for  $H$ .

This value fits in with a previous analysis of a flattened dark halo of our Galaxy (Sciama 1999) where it was shown that 3kpc is the smallest allowed value for  $H$  (cf. Sackett 1999). In particular this value is just compatible with recent estimates of the total density  $\rho$  of matter near the sun, as derived from the vertical motions of nearby stars deduced from HIPPARCOS data (Pham 1997, Creze et al 1998, Holmberg & Flynn 1998). Taking  $\sim 100 M_\odot \text{pc}^{-2}$  for the column density of dark matter at the sun on one side of the galactic plane (Binney and Tremaine 1987) one would have with our adopted value of  $H$  a dark matter density near the sun of  $\sim 0.03 M_\odot \text{pc}^{-3}$ . Taking  $1.1 M_\odot \text{pc}^{-3}$  as the upper limit of  $\rho$  from the HIPPARCOS data, and  $0.04 M_\odot \text{pc}^{-3}$  for the densities of both stars and visible gas near the sun, one just arrives at a consistent set of values. Since each MC is assumed to have a mass  $\sim 10^{-3} M_\odot$ , it follows that there are  $\sim 30$  MC's  $\text{pc}^{-3}$  near the sun.

One may speculate on the origin of the large flattening of the MC distribution. One contributing factor could be the accretion of interstellar gas subsequent to the formation of the MC's. Since the column density of an MC in our adopted model is  $\sim 60 \text{ gm cm}^{-2}$  or  $\sim 10^{25} \text{ H}_2 \text{ molecules cm}^{-2}$ , which is much greater than the column density of the diffuse gas in the Galaxy, and since the MC's are moving supersonically through this gas, they would simply drill holes in the gas and scoop up all the material in their path (Tenorio - Tagle et al 1987, Comeron & Torra 1992, Santillan et al 1999). Accordingly their column density would increase at the rate  $n_g v$  per unit time, where  $n_g$  is the number density of the gas. Allowing for an increase in  $n_g$  in the past, and integrating over a time of  $10^{10}$  years, one arrives at a total accreted column density in  $\text{H}_2$  of  $\sim 3 \times 10^{24} \text{ cm}^{-2}$ . This is not much less than the present column density of an MC, and given the various uncertainties in the calculation it is reasonable to suppose that the vertical component of the motion of the MC's may have been appreciably damped, thereby helping to give rise to their flattened distribution.

Another important consequence of this accretion of interstellar gas concerns the composition of the MC's. They

are sometimes considered to have a primordial composition, consisting primarily of H and He. However, the presence of a significant abundance of heavy elements in the MC's will be crucial for our discussion of their far  $i - r$  emissivity. As we shall see, we will not need a full solar metallicity, but a significant contamination could arise from the accreted gas. Another source of metallicity will be described in the next section.

### 3 THE FORMATION EPOCH OF THE MC'S.

A clue to the likely formation epoch of the MC's can be found by noting that if the dark matter in all the galaxies is baryonic then the resulting mean density of these baryons at the present epoch is close to the value implied by big bang nucleosynthesis (BBNS) (Fukugita, Hogan & Peebles 1998). Apart from solving the well-known problem "where are the baryons?", this result is helpful for determining the formation epoch of the MC's because it has recently been realized that at a red shift  $\sim 3$  the amount of ionised gas believed to be associated with the much smaller amount of neutral gas contained in the Lyman  $\alpha$  clouds is again close to the BBNS value (Rauch & Haehnelt 1995, Giallongo, Fontana & Madau 1997). Moreover, the evolution of the Lyman  $\alpha$  cloud system at lower redshifts is so rapid that the implied amount of gas decreases with decreasing red shift on the fast timescale of 1 Gyr. Giallongo et al speculate on why the gas is disappearing so fast and suggest that it may be driven out of the Lyman  $\alpha$  clouds by supernova explosions. From our point of view it is natural to suggest that one is here observing the formation of the MC's. This suggestion would imply that most Lyman  $\alpha$  clouds are associated with galaxies. This possibility has already been much debated in the literature and remains controversial. A recent supporting discussion (with references to earlier work) has been given by Ortiz-Gil et al (1999).

One significance for us of these ideas is that at a red shift of 3 Lyman  $\alpha$  clouds already contained an observable abundance of metals (eg. Songaila 1997). This provides a second reason for expecting MC's in the Galaxy to contain an appreciable abundance of metals.

### 4 THE ATTENUATION DEPTH OF MC'S FOR COSMIC RAYS.

If galactic cosmic rays penetrate the MC's, the question arises of the attenuation length of the clouds. Let us first consider whether this penetration actually occurs. This question has already been much discussed, both theoretically and observationally, for the known molecular clouds in the Galaxy (e.g. Cesarsky & Volk 1978, Lebrun & Paul 1978, Cesarsky 1980, Berezhinskii et al 1990). In their reviews of this question Cesarsky (1980) and Berezhinskii et al (1990) considered that  $\gamma$  ray observations show conclusively that cosmic rays do enter molecular clouds.

Of course MC's are moving through the interstellar medium much faster than the known molecular clouds, and it is not clear whether penetration occurs in this case. It would be very difficult to carry out a convincing theoretical calculation to decide this question a priori and it may be better simply to assume that penetration does occur, and

then compare the implied consequences with observation.

There are in fact a number of quite different consequences which can be tested observationally at the present time, in particular the lifetime  $t_0$  for cosmic ray nuclei, and the  $\gamma$  ray and far  $i - r$  emissivity of the MC's. In addition their heating and cooling rates determine their temperature  $T$ , which is a basic parameter of our adopted model.

The crucial property of the MC's which controls all these phenomena is their column density  $N$ . In our adopted model  $N \sim 60 \text{ gm.cm}^{-2}$  or  $N_{\text{H}_2} \sim 10^{25} \text{ H}_2 \text{ molecules cm}^{-2}$ . This is much larger than the grammage required to destroy by spallation the cosmic ray nuclei ( $\sim 8 \text{ gm.cm}^{-2}$  for light and medium mass nuclei and  $\sim 2 \text{ gm.cm}^{-2}$  for heavy nuclei). It is also comparable to both the stopping power of  $\text{H}_2$  for  $\sim 1 \text{ GeV}$  protons due to their ionisation losses, and to the attenuation length for the hadronic interactions of GeV protons leading to the production of pions (pionisation losses) (Review of Particle Physics 1996). Thus on the one hand the heat input into the MC's is large. On the other hand, self-shielding effects in the MC's will be important. Both these facts are used in the present paper, but a full discussion of them would require extensive calculations which will be left for later papers in this series.

We now consider the calculation of the survival time  $t_0$ , and leave for the next section a discussion of the energetics of the MC's. As a cosmic ray nucleus propagates in the Galaxy it will be scattered by magnetic irregularities in the interstellar medium. The mean free path associated with this scattering process is believed to be about 0.1 pc (Berezhinskii et al 1990). In fact the resulting change of direction of a cosmic ray does not matter for the present calculation since it is being assumed that the distribution of clouds is approximately uniform on the relevant length scale. For a relativistic cosmic ray nucleus the mean time  $t_0$  for it to collide with an MC and be fragmented is given by  $(\pi r^2 n c)^{-1}$ . For  $r \sim 10^{14} \text{ cm}$  and  $n \sim 30 \text{ pc}^{-3}$  one obtains  $t_0 \sim 10^{15} \text{ sec}$ . This is just the value which has been derived for the mean ages of the radioactive cosmic ray nuclei  $\text{Be}^{10}$  and  $\text{Al}^{26}$  with energies  $\sim 1 \text{ GeV/nucleon}$  (Simpson & Connell 1998, Webber & Soutoul 1998). Of course  $n$  would be expected to decrease with height above the galactic plane, but since the storage height of cosmic rays is believed to be less than the 3 kpc scale height of the MC's (Berezhinskii et al 1990) this should be a small effect. We therefore postulate that collision with MC's provides the main loss process for cosmic ray nuclei rather than leakage out of a confinement volume.

For subrelativistic nuclei of velocity  $v$  we would expect that  $t_0 \propto 1/v$ . While the relevant data are not very accurate there is some indication that indeed more  $\text{Be}^{10}$  has decayed the lower its velocity (Simpson 1983).

For cosmic ray protons the situation is different. As we have seen the column density of an MC is of the same order as the attenuation length of  $\text{H}_2$  for GeV protons. Hence the collision of such a proton with an MC would degrade its energy but would not destroy it. Allowance should also be made for the smaller fractional energy losses of the more energetic protons. Again detailed calculations are needed, but it is clear that the effective lifetime of cosmic ray protons in the GeV energy range could exceed  $t_0$  by a significant factor. Moreover much more energetic protons could have avoided appreciable energy losses over the whole lifetime of the Galaxy. Unfortunately, since the source spectrum of the

cosmic rays is unknown, it is not possible to test this idea observationally.

## 5 THE ENERGETIC OF MC'S

We have already noted that, because MC's in our adopted model have a column density  $\sim 60 \text{ gm.cm}^{-2}$ , optical depth effects would be important for both ionisation and pionisation losses. Consider first the heating of the MC's by cosmic ray interactions. Since  $60 \text{ gm.cm}^{-2}$  of  $\text{H}_2$  can just stop 500 Mev protons due to their ionisation losses (Review of Particle Physics 1996) we need to know the energy density  $\epsilon_{\text{CR}}$  in cosmic rays of up to about this energy. The effective heating rate  $J$  per  $\text{H}_2$  molecule in an MC will then be  $\sim \epsilon_{\text{CR}} c N_{\text{H}_2}^{-1}$ . For  $\epsilon_{\text{CR}} \sim 0.2 \text{ eV cm}^{-3}$  (Webber 1998) and  $N_{\text{H}_2} \sim 10^{25} \text{ cm}^{-2}$  one obtains  $J \sim 10^{-27} \text{ ergs.sec}^{-1} \text{H}_2^{-1}$ . There will also be a contribution to  $J$  from electrons produced by pion and muon decay in the clouds, but for a rough estimate this contribution can be neglected.

To determine the cooling rate one must know the constitution of the MC's. As discussed previously it will be assumed that the MC's are contaminated by heavy elements, although any dust particles in them must have fallen to their centres to avoid opacity effects which have not been observed (Gerhard & Silk 1996). The steady state abundances of different molecules in the MC's represent the outcome of a large number of chemical reactions triggered by cosmic ray ionisation, and have recently been computed for clouds nearly as dense as our MC's by Sternberg & Dalgarno (1995) and by Neufeld, Lepp & Melnick (1995). The latter authors also made extensive calculations of the resulting cooling rate due to molecular line emission excited by collisions with  $\text{H}_2$ , although they used a somewhat small cosmic ray ionisation rate. The key point is that, for the large densities and optical depths involved in very dense clouds, many of the emission lines of a considerable number of molecular species become optically thick. An MC is thus rather like a star, which is opaque to the radiation produced by its internal heat sources. The important consequence for us is that even molecular species with a relatively small abundance will contribute significantly to the emissivity if they are abundant enough for their emission to be optically thick.

Neufeld et al (1995) calculated the emission in all these hundreds of optically thick lines, and so derived the cooling rate of clouds which are heated and ionised by cosmic rays, and are nearly as dense as our MC's. They represented their results graphically (for a number of final temperatures) as a function of the density  $n_{\text{H}_2}$  of  $\text{H}_2$  molecules in the core of the clouds. Gerhard & Silk (1996) represented this cooling rate analytically in the form  $2.1 \times 10^{-28} T_{10}^{2.6} / n_{11}^{0.3} \text{ ergs.sec}^{-1} \text{H}_2^{-1}$ , where  $T = 10 T_{10} \text{ K}$  and  $n_{11} = 10^{11} n_{\text{H}_2}$ , and used it to determine the temperature of an MC. For our choice of heating rate and MC parameters one obtains  $T_{10} \sim 1.9$ , which would satisfy the virial theorem for the clouds (Draine 1998). However this calculation should be repeated with a revised cooling rate based on the larger cosmic ray ionisation rate being used here.

The strongest emission lines would lie in the far  $i-r$ , with a cut-off at about 1000 GHz or  $300 \mu$  for our choice of  $T$ . There would be hundreds of lines in this frequency or wavelength range, and the resulting spectrum would look

like a continuum to any detector unable to resolve them. To estimate the integrated intensity of this continuum for the whole Galaxy one would need to know the spatial distribution of both the cosmic rays and the MC's. To avoid obtaining a result which is too model dependent we prefer to proceed semi-empirically by relating the far  $i-r$  emission of the MC's to their  $\gamma$  ray emission. As we shall see, it is possible to use observational data on the  $\gamma$  ray emission of the Galaxy as a partial substitute for a spatial model.

It is pointed out in the next section that the observed  $\gamma$  ray emission in the plane of the Galaxy contains an excess component for  $\gamma$  ray energies  $> 1 \text{ GeV}$ . We propose to identify this excess as pionic  $\gamma$  rays emitted by MC's. Now the  $\gamma$  ray emissivity of the MC's can be related to their far  $i-r$  emissivity via a simple conversion factor. To derive this factor we note from Mori (1997) that, for a standard cosmic ray flux, the number of pionic  $\gamma$  rays produced with energies  $> 1 \text{ GeV}$  is  $3.2 \times 10^{-26} \text{ sec}^{-1} \text{H}_2^{-1}$ . Because of self-shielding in the MC's this flux must be reduced to  $1.6 \times 10^{-26} \text{ sec}^{-1} \text{H}_2^{-1}$  (see Section 6). Since the far  $i-r$  flux  $\sim 10^{-27} \text{ ergs} \cdot \text{sec}^{-1} \text{H}_2^{-1}$ , it follows that the conversion factor  $\sim 0.06 \text{ ergs per photon}$ . This factor depends on the energy spectrum of the cosmic rays but not on their absolute flux.

## 6 THE $\gamma$ RAY EMISSIVITY OF THE MC'S

We saw in Section 2 that, in our adopted model, the mean density of matter due to the MC's near the sun is nearly the same as that of the visible matter in the interstellar medium. At first sight this near-equality would lead to an approximate doubling of the  $\gamma$  ray emissivity in the galactic plane since pionic  $\gamma$  rays dominate the flux for energies exceeding 300 Mev. Yet in their detailed analysis of the EGRET data Hunter et al (1987) found good agreement between their model, using only visible matter sources, and the observational data in the galactic plane, for  $\gamma$  ray energies  $< 1 \text{ GeV}$ . This apparent discrepancy with our model can be attributed to self-shielding effects. According to Mori (1997) pionic  $\gamma$  rays of energy  $< 1 \text{ GeV}$  are produced mainly by incident protons whose energy lies in the range 1–3 GeV. These protons are heavily degraded in the MC's, so that a substantial fraction of the  $\text{H}_2$  molecules would be shielded from them. On the other hand pionic  $\gamma$  rays of energy  $> 1 \text{ GeV}$  are mainly produced by protons with energy  $> 3 \text{ GeV}$ , whose fractional energy loss is smaller. Thus shielding effects would be less important for these higher energy protons. Accordingly some sign of the presence of additional higher energy  $\gamma$  rays would be expected in the observational data, if our model is correct.

In fact, as already mentioned, Hunter et al (1987) found a 60% excess in the observed flux in the galactic plane over their model calculations for  $\gamma$  rays with energies  $> 1 \text{ GeV}$ , and were unable to give a satisfactory account of this discrepancy. Other attempts to explain the excess (Mori 1997, Strong, Moskalenko & Reiner 1998) have also not been successful. We therefore suggest here that the excess is due to pionic  $\gamma$  rays emitted by MC's powered by cosmic rays. The fact that the excess is only 60% rather than closer to a factor 2 can be taken to indicate some self-shielding even for the higher energy protons involved. The corresponding amount of self-shielding was used in the previous section to derive the conversion factor from  $\gamma$  rays to far  $i-r$  radiation.

We may add that the mean free path of a 1 GeV  $\gamma$  ray in  $H_2$  is  $85 \text{ gm.cm}^{-2}$  (Review of Particle Physics 1996), so that the correction for attenuation of such a  $\gamma$  ray in an MC is not large. However, if we wish to identify the EGRET excess with  $\gamma$  rays from MC's we must impose a strong upper limit on the column density  $\eta$  of  $\sim 100 \text{ gm cm}^{-2}$ . On the other hand, the absence of an EGRET excess below 1 GeV imposes a lower limit on  $\eta$  of  $\sim 30 \text{ gm.cm}^{-2}$ . Thus  $\eta$  is somewhat constrained.

According to the recent analysis of Dixon et al (1998) the EGRET data also show that our Galaxy possesses a  $\gamma$  ray halo. In this case the relevant column density in the MC's would be much greater than that in visible interstellar matter, and De Paolis et al (1999 a, b) have already attributed this  $\gamma$  ray flux ( $\sim 10^{-6} - 10^{-5}$ ) photons  $\text{cm}^{-2}\text{sec}^{-1}$  above 1 GeV) to MC's in the galactic halo. In the next section our conversion factor will be applied to this flux as well as to the flux in the plane. We shall find that the resulting far  $i-r$  flux is compatible with observation at high Galactic latitudes as well as in the plane.

## 7 THE FAR $i-r$ EMISSIVITY OF THE MC'S

In this section we estimate the far  $i-r$  emissivity of the MC's and compare the result with observation. To do this we use the conversion factor between the far  $i-r$  and  $\gamma$  ray fluxes from MC's arrived at in the previous section. To illustrate the method we estimate the average far  $i-r$  flux  $F_{ir}$  in the range of directions  $|b| < 2^\circ$ ,  $\ell = 45^\circ$ . A detailed study of various galactic latitudes and longitudes, and of the accompanying spectral effects, will be deferred to a later paper of this series.

In our chosen range of directions the average 60% excess  $\gamma$  ray flux  $\sim 3 \times 10^{-4}$  photons  $\text{cm}^{-2}\text{sec}^{-1}$  (Hunter et al 1987). Accordingly, in these directions  $F_{ir} \sim 1.8 \times 10^{-5} \text{ ergs cm}^{-2}\text{sec}^{-1}$ . As already explained, this far  $i-r$  radiation would be concentrated in hundreds of emission lines lying mainly in a range dictated by a Rayleigh-Jeans cut-off at low frequencies and a temperature cut-off at high frequencies. In our model, with  $T \sim 20 \text{ K}$ , this high frequency cut-off would be in the vicinity of  $1000 \text{ GHz}$  ( $300 \mu$ ). This radiation would look like a smooth continuum to a detector unable to resolve the closely spaced emission lines.

Just such a diffuse emission component, cutting off at  $\sim 600 \text{ GHz}$ , has in fact been discerned in our Galaxy, in the form of excess radiation over a warm dust component. This dust component has been fitted with a single temperature in the range  $16-21 \text{ K}$  (for an emissivity law  $\nu^2$ ). The excess component has been detected and interpreted by a number of workers (Page, Cheng & Meyer 1990, Meinhold et al 1993, Reach et al 1995, Lagache et al 1998, 1999, Finkbeiner, Davis & Schlegel 1999). For our purposes it is convenient to use the analysis of the COBE group (Reach et al 1995), whose figure 7 shows clearly the excess component in the direction  $|b| < 3^\circ$ ,  $\ell = 45^\circ$ , as a function of frequency. This component has cut-offs at 150 and 600 GHz. Its intensity near its peak  $\sim 1 \text{ MJy ster}^{-1}$ , which converts to a total flux in this bandwidth  $\sim 2 \times 10^{-5} \text{ erg cm}^{-2}\text{sec}^{-1}$ . All these properties agree well with those derived above for the far  $i-r$  emission from MC's in this direction.

The same test can be carried out at high galactic latitude, but with less precision. In this case the EGRET

data have been analysed by Dixon et al (1998) to give for the photon flux above 1 GeV the range  $10^{-6} - 10^{-5}$  photons  $\text{cm}^{-2}\text{sec}^{-1}$ . As we have seen, this flux has already been attributed to MC's by De Paolis et al (1999 a, b). The corresponding far  $i-r$  flux would be in the range  $6 \times 10^{-8} - 6 \times 10^{-7} \text{ erg cm}^{-2}\text{sec}^{-1}$ . According to Reach et al (1995) the excess far  $i-r$  component at high latitudes  $\sim 0.03$  of the value close to the galactic plane, that is, about  $6 \times 10^{-7} \text{ erg cm}^{-2}\text{sec}^{-1}$ . This value just fits in with the range expected from the  $\gamma$  ray data if MC's are the source of the high latitude far  $i-r$  excess.

A further possible observational test of the MC model concerns the far  $i-r$  emission from a single MC, which to many detectors would look like a point source. With 30 clouds  $\text{pc}^{-3}$  close to the sun, the nearest MC's would be less than a parsec away. In our model an average MC one parsec away would have a flux density  $S_{850}$  at  $850 \mu \sim 0.5 \text{ Jy}$ . This would be a bright source for SCUBA, which observes at  $850 \mu$  (Holland et al 1999), but unfortunately this detector has a very small field of view. In typical recent work areas  $\leq 100 \text{ arc min}^2$  were surveyed (eg. Barger et al 1999 a). In such surveys point sources with  $S_{850}$  in the range  $1-10 \text{ mJy}$  were detected (for a review of these observations see Sanders 1999). Most of these sources are believed to be galaxies with red shifts greater than 1, although the identification process is a difficult one (Barger et al 1999 b, Richards 1999, Sanders 1999, Smail et al 1999). The number of these galaxies with flux densities  $S_{850}$  exceeding a given limit is subject to very large evolutionary effects, of order  $10^3$ , as a result of which less than 1 percent of the point sources brighter than  $1 \text{ mJy}$  would be MC's. It would be difficult to identify these sources with sufficient completeness to pick out this small proportion of MC's. However, one way of testing for such a source would be to measure its flux density at  $450 \mu$ , which SCUBA can do. This wavelength is close to the temperature cut-off in the MC spectrum, so that for an MC  $S_{450} \lesssim S_{850}$ . By contrast, the few sources so far successfully measured at  $450 \mu$ , which are presumably galaxies, have  $S_{450} \sim 4 S_{850}$  (Blain et al 1999, Eales et al 1999).

For the future we note that Planck would easily be able to observe the nearby MC's with  $S_{850} \sim 1 \text{ Jy}$ , and so test our prediction that there should be  $\sim 10$  sources over the whole sky with  $S_{850} > 1 \text{ Jy}$ . It could also carry out a study of the  $\log N - \log S$  relation of these sources and of their fluxes at other wavelengths such as  $450 \mu$ .

## 8 CONCLUSIONS

If the dark matter in the Galaxy consists mainly of molecular clouds (MC's) and if cosmic rays can penetrate these clouds, there would be a number of observable consequences. This paper has discussed four such consequences for a favoured model of the clouds.

- (i) Relativistic cosmic ray nuclei should have a survival time in the Galaxy  $\sim 10^{15} \text{ sec}$ .
- (ii) There should be an excess in the diffuse  $\gamma$  ray flux in the galactic plane, for  $\gamma$  ray energies exceeding  $\sim 1 \text{ GeV}$ , of order 50% over that due to known sources.
- (iii) There should be an excess in the diffuse far  $i-r$  flux in the Galaxy over that radiated by warm dust. This excess flux should have a cut-off for wavelengths less than about

$450\mu$ , and should decrease with galactic latitude. Its flux density at  $850\mu$  close to the galactic plane at a longitude of  $45^\circ$  should be about  $1\text{MJy ster}^{-1}$ , corresponding to an energy flux  $\sim 2 \times 10^{-5}\text{erg cm}^{-2}\text{sec}^{-1}$ .

(iv) The MC's would be discrete sources of far  $i-r$  radiation, with about 10 sources in the sky having  $S_{850} > 1\text{Jy}$ . These sources would be expected to exhibit a Euclidean  $\log N - \log S$  relation for uniformly distributed sources down to a flux level much less than  $1\text{mJy}$ , the present approximate limit of the SCUBA counts. At this lower flux level less than 1 per cent of the sources at  $850\mu$  should be MC's. These MC's would be characterised by having  $S_{850} \geq S_{450}$ , unlike galaxies which have  $S_{850} \sim \frac{1}{4}S_{450}$ .

The first three of these consequences are in agreement with observation. The fourth consequence is not contradicted by the present SCUBA data, and can be tested by forthcoming measurements such as those planned for the Planck surveyor.

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